

## On the detectability of cosmic ray electron spectral features in the microwave/mm-wave range

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Recent measurements of cosmic ray electron energy spectra suggest that above 10 GeV there may be deviations from a single power law spectrum. There are hints (ATIC) for a bump occurring between 100 GeV and 1 TeV, meaning that there might be more high energy electrons than expected. Whether these electrons are produced within pulsar magnetospheres, or due to Dark Matter annihilation or decay, this is still matter of debate. Understanding the nature of these ultra high energy particles is a difficult task that can be fulfilled using all the available astrophysical observables. We investigate how different energy spectra produce different observable manifestations in the radio/microwave/mm-wave domain, where corresponding deviations from a synchrotron power law could appear. We raise the question around the detectability of these possible radio spectral features, which may be interesting for a wide scientific community including astrophysicists and scientists working on foregrounds removal for CMB experiments.

*Keywords:* Cosmic rays; synchrotron radiation; diffuse radio continuum.

### 1. Science case

Recently several experiments have pointed out interesting features in the measured energy spectrum of the  $e^+$  and  $e^-$  components of cosmic rays. In particular, we recall here the positron excess detected by Pamela<sup>1</sup>, the excess of electron counts ( $e^+ + e^-$ ) between 100 GeV and 1 TeV detected by Fermi<sup>2</sup>, and the bump in the cosmic ray electron (CRE) spectrum, centered around  $\sim 500$  GeV, detected by ATIC<sup>3</sup> (not confirmed by H.E.S.S. low energy analysis<sup>4</sup>). The observational picture will be probably improved after the observations of AMS-02<sup>5</sup> (which will be operating in February 2011), due to the large acceptance and accuracy of the apparatus and to the long

operation time (at least ten years). In this work we do not look for possible interpretations of these data, rather we study the possibility of using radio observations to confirm the above CREs spectral features. In particular, we concentrate on the evaluation of CRE synchrotron emission in a galactic environment, with typical values of the magnetic field strength of  $1 - 5 \mu\text{G}$ .

Due to the explorative aims of this study, we limit our attention to the intensity and degree of polarization of radiation produced by an ensemble of electrons, in the hypothesis of homogeneity of the galactic magnetic field on scales greater than the gyro-radius, and discuss the properties of radiation at the source, not taking into account radiative transfer through the interstellar medium (ISM), which affects both intensity and degree of polarization. This issue can be the object of a subsequent paper. Here we point out the relevant frequency bands for possible observations and signatures that may allow one to disentangle their signal from contaminants like thermal dust emission, peaking in the sub-mm range. We show also that expected signals are not a limiting foreground for Cosmic Microwave Background experiments, being expected at  $\sim 1 \text{ THz}$  and above. Finally we discuss a few observational aspects of some astrophysical sources which could be used as targets for this investigation.

## 2. Method

The connection between diffuse radio emission and cosmic ray propagation within the Galaxy was firmly established in the Sixties<sup>6</sup>. Here we recall the basic results concerning the single particle synchrotron emission, and the emission of an ensemble of particles, with a known energy spectrum, propagating in a uniform magnetic field<sup>7</sup>. A charged particle (an electron, from now on) moving in a region pervaded by a uniform magnetic field describes an helical trajectory, with a pitch angle  $\alpha$  between the velocity vector and the magnetic field lines. Being accelerated, it loses energy by radiation. If the velocity of the charge is relativistic, the radiation is strongly beamed, and is almost completely emitted within a cone of aperture  $\sim 1/\gamma$ , where  $\gamma$  is the Lorentz factor, typically  $\geq 10^3$  for the electrons associated to the observed radio continuum of the Galaxy. This cone is centered around the instantaneous velocity of the particle, sweeping periodically the line of sight of the observer. Only in a short ( $\sim 1/\gamma$ ) fraction of the gyration period, when the line of sight lies within the radiation cone, the observer registers a pulse of radiation. The Fourier transform of this pulse, in the observer's frame, is a continuous spectrum and most of the radiation is concentrated in a narrow peak at frequency  $\nu \sim \gamma^2 \nu_g$ , with gyro-frequency

$\nu_g = eB/2\pi m_e$ , where  $B$  is the magnetic field,  $e$  the charge of the electron, and  $m_e$  its mass.

Following Longair, we introduce a cartesian frame suitable for the description of synchrotron radiation, including its polarization. To this purpose, let's consider a plane orthogonal to the wave vector  $\mathbf{k}$ : we can project the magnetic field on this plane. Let's call  $B_{\perp\mathbf{k}}$  the projected component. We can form a triad with a versor parallel to  $B_{\perp\mathbf{k}}$  (components in this direction will be labeled with  $\parallel$ ), one orthogonal to both  $B_{\perp\mathbf{k}}$  and  $\mathbf{k}$  (components in this direction will be labeled with  $\perp$ ), and  $\mathbf{k}$  itself. In this frame, synchrotron emissivities of a single electron in the two polarizations are:

$$\begin{aligned} j_{\perp}(\nu) &= \Gamma B_{\perp} \sin \alpha [F(\nu/\nu_c) + G(\nu/\nu_c)] \\ j_{\parallel}(\nu) &= \Gamma B_{\perp} \sin \alpha [F(\nu/\nu_c) - G(\nu/\nu_c)] \end{aligned}$$

where: (1)  $\Gamma \cong 1.86 \times 10^{-26}$  W/THz; (2)  $\nu_c = 3\gamma^2\nu_g \sin(\alpha/2)$  is the critical frequency; (3)  $F(x)$  and  $G(x)$  are spectral functions defined through modified Bessel functions as  $F(x) = x \int_x^{\infty} K_{5/3}(z) dz$  and  $G(x) = x K_{2/3}(x)$ . Now, if we have  $N(E)dE$  electrons per energy interval  $dE$ , per unit volume, the spectral intensity per unit volume radiated by the cloud of electrons is  $I(\nu) = \int_0^{\infty} j(x)N(E)dE$ , where  $x = \nu/\nu_c = x(E, B)$  and  $j = j_{\perp} + j_{\parallel}$ . Therefore we arrive at a useful integral:

$$I(\nu) = \frac{\kappa m_e c^2}{\sqrt{6\nu_g \sin \alpha}} \sqrt{\nu} \int_0^{\infty} j(x) N[E(x)] x^{-3/2} dx \quad (1)$$

that can be computed analytically in some remarkable cases (e.g.  $N(E) \propto E^{-\beta}$ ), but that we compute numerically in order to deal with arbitrary energy distributions. Here  $\kappa$  is normalization factor. An average on the pitch angle  $\alpha$  in the range  $(0, \pi)$  will lead to the results presented in the next section. If we deal separately with the intensity emitted in two orthogonal polarizations, we can compute its degree of linear polarization, that is:

$$\Pi(\nu) = \frac{I_{\perp}(\nu) - I_{\parallel}(\nu)}{I_{\perp}(\nu) + I_{\parallel}(\nu)}. \quad (2)$$

In terms of Stokes parameters,  $\Pi = \sqrt{Q^2 + U^2}/I$ . Its value may be up to  $\sim 75\%$  for a power law distribution of electrons with slope around  $-3$ . Nevertheless this value is strictly an upper limit, being obtained without considering radiative transfer effects occurring in the ISM, leading to depolarization. Conversely, the degree of circular polarization of an ultra-relativistic electron is vanishingly small, scaling as  $1/\gamma$ : therefore, we do

not consider  $\Pi_c$  in the following discussion. Like the intensity, the degree of polarization is computed numerically.

### 3. Results

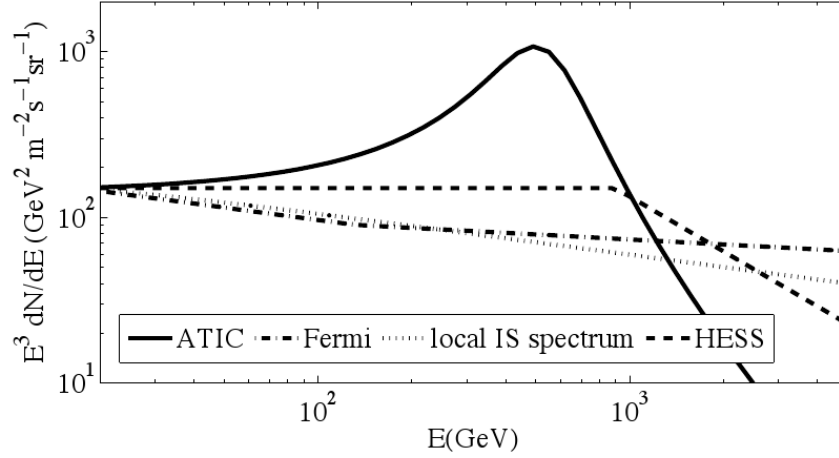


Fig. 1. Different analytical description of the electron spectra used for calculating synchrotron spectra. All these spectra are normalized at the value of  $150 \text{ GeV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$  at 10 GeV energy.

The calculations described in the previous sections (equation 1 and 2), have been implemented using different electron spectra. In particular we used: (1) the description of the local interstellar spectrum by Zhang & Cheng<sup>8</sup>; (2) a broken power law to describe H.E.S.S. high energy knee<sup>4</sup>; (3) a synthetic representation of a Fermi-like spectrum exhibiting a hardening (from a  $-3.2$  to a  $-3.0$  slope) around  $\sim 100 \text{ GeV}^2$ ; (4) a synthetic representation of an ATIC-like spectrum<sup>3</sup> with a lorentzian-shaped bump on a constant slope ( $\beta = -3$ ) background. This oversimplified analytical description is enough to capture the main features arising in synchrotron emission. All these spectra have been normalized at a common value of  $E^3 J(E)$  of  $150 \text{ GeV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$  at 10 GeV, and are shown in Fig.1 .

In turn, the synchrotron spectra obtained from these sources are ultimately normalized to a measured value of the minimum synchrotron sky brightness at  $\delta = +42^\circ$  and  $RA \simeq 10h$  (Galactic halo), using the results of the TRIS experiment presented in Tartari et al.<sup>9</sup>: our reference brightness

at 1 GHz is  $3.8 \times 10^4$  Jy/sr. The obtained synchrotron spectra are shown in Fig.2, while in Fig.3 we show the degree of linear polarization.

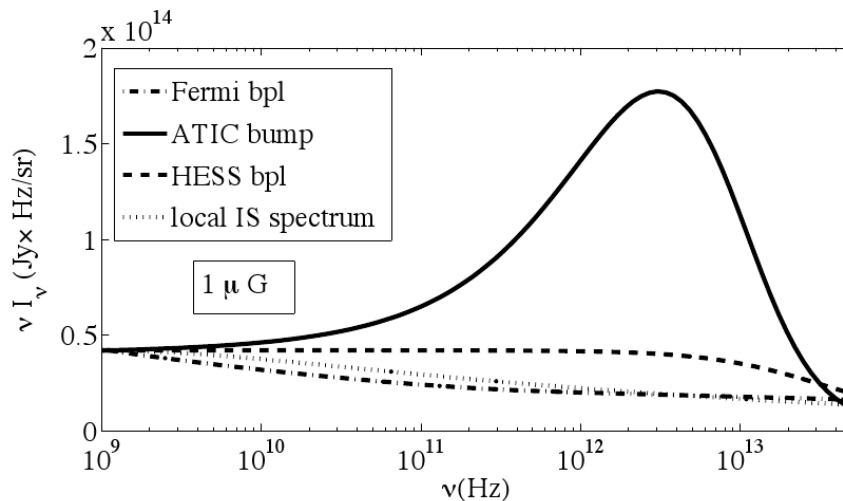


Fig. 2. Spectra of the synchrotron emission forecasts for the different CRE populations. These intensities are normalized to a radio brightness of  $3.8 \times 10^4$  Jy/sr measured by the TRIS experiment in a purely synchrotron emitting region on the Galactic halo at  $\delta = +42^\circ$  and  $RA \simeq 10h$ . A Galactic magnetic field of  $1\mu\text{G}$  is assumed.

In Fig.2 and 3 we show only the values obtained for a magnetic field of  $1\mu\text{G}$ . Results at 3 and  $5\mu\text{G}$  are similar except that all the features moves at higher frequency as expected.

#### 4. Discussion and Conclusions

We have shown that the features in synchrotron intensity and polarization produced by  $> 100$  GeV electrons fall into the sub-mm wave/far IR regime (therefore, they are not an issue when removing foregrounds from CMB maps). Moreover a bump in the electron spectrum (ATIC) modulates significantly (more than 10%) the degree of synchrotron linear polarization at frequencies around 1 THz. Unfortunately, the Galactic dust, through its grey-body emission,  $I_d(\nu) = k_d(\nu/\nu_0)^{\beta_d} BB(T_d)$ , completely dominates the sky brightness in these bands. In Fig.4 we show the expected brightness of a clean region of the sky normalized (through  $k_d$  emission coefficient) at the DIRBE<sup>10</sup> 100  $\mu\text{m}$  channel. We assumed a dust temperature  $T_d = 20$  K,

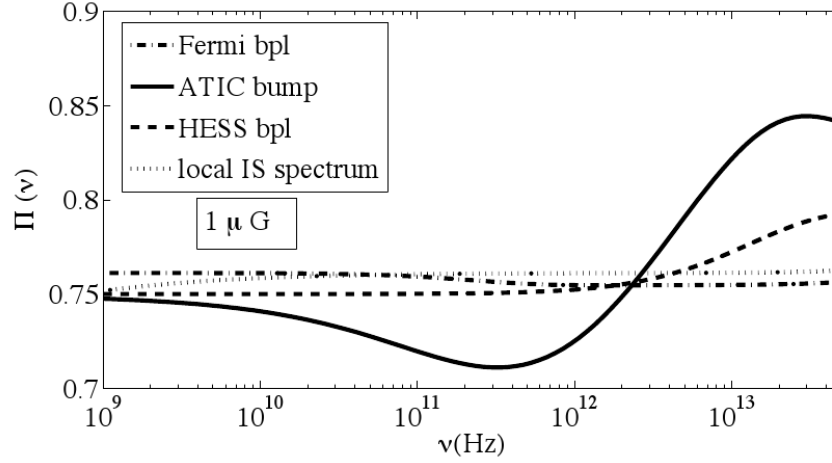


Fig. 3. Degree of linear polarization ( $\Pi$ ) *vs* frequency. A Galactic magnetic field of  $1\mu\text{G}$  and the maximum degree of linear polarization are assumed.

and grey-body emissivity scaling as  $\nu^{\beta_d}$  ( $\beta_d = 1.7$ ). We see that dust signal overcomes the synchrotron one by several orders of magnitude.

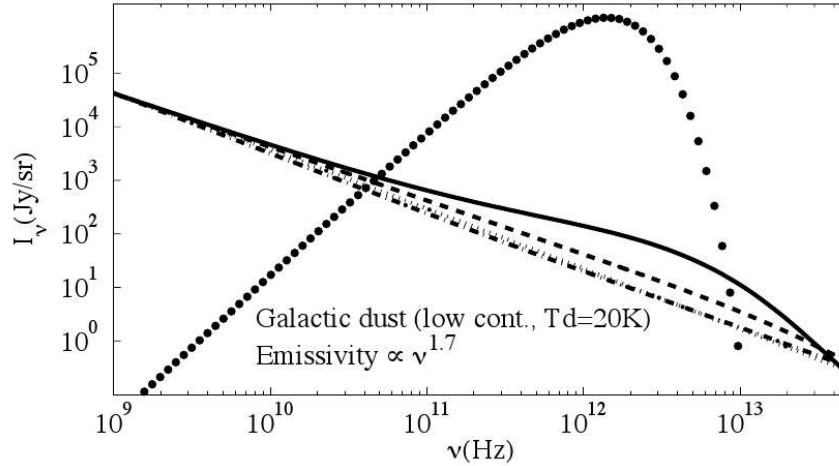


Fig. 4. Synchrotron brightness corresponding to different electron spectra (same line style as in fig.2 and 3.). The filled circles correspond to the emission of cold (20 K) dust in a low contamination region of the sky, normalized to the measurements of the  $100\mu\text{m}$  DIRBE channel.

This is just an example, since in general dust contamination depends on the region observed (different temperature, density and composition of dust). Let's now consider different sources of the observed CRE excess.

*A) Dark Matter decay or annihilation in our galaxy.* The distribution of synchrotron radiation is probably similar to the expected Dark Matter distribution in the galactic halo. We expect a smooth distribution with a maximum of intensity in direction of the galactic center decreasing away from it. The best directions of observations are far from the galactic disk, where the synchrotron emission of the background electrons and the thermal emission of the interstellar dust are faint and more uniform. This is the situation we have considered to estimate the signals shown in Fig.4: above 100 GHz thermal dust emission is the dominating signal also far from the Galactic disk. Therefore it is difficult to imagine a detection of a diffuse, smoothly varying synchrotron signal coming from our own Galaxy, such as what could be associated to a Dark Matter halo. In this case, also considering the typical polarization signatures of synchrotron radiation, the removal of the thermal background would be extremely difficult, despite the small degree of linear polarization of thermal dust emission.

*B) Electrons from Pulsar or SNR.* A galactic source like a pulsar or a SNR can be found (much more easily) on the galactic disk. Here both the synchrotron emission of the background electrons and the thermal emission of the interstellar dust are stronger respect to the signals coming from the halo and shown in Fig.4. Dust emission is expected to increase more than synchrotron. In addition the angular distribution is also more anisotropic. This situation is compensated by a possible *boost factor* enhancing the synchrotron signal coming from these sources, if CRE come out along the direction of observation. In fact electrons radiate only towards the speed vector, and we detect their radiation only if this direction is aligned with our line of sight. Besides electrons originated by these sources come to the Earth position through a diffusion process, because the gyro-radius, in the interstellar magnetic field even at energy up to 1 TeV, is much smaller than the distance of the closest candidate sources. In addition around these sources the magnetic field is far from uniform. This *boost factor* could be large up to the Lorentz factor  $\gamma$ , but we must take into account also that the detected CRE could come from sources not radiating in the direction of our line of sight. In conclusion one could map a region surrounding a galactic source, like a pulsar or a SNR, looking for an anisotropic signal at small angular scales. In this case the background subtraction could be easier, in particular if we look at the spectral feature in the polarized signal.

*C) Electrons in extragalactic sources.* An alternative approach is to observe extragalactic radio sources: spiral or elliptical galaxies. In fact we expect the same phenomenology, regarding cosmic rays and synchrotron radiation, in external galaxies as in our own. Also regions surrounding AGNs could be used as target to observe features in the synchrotron radiation (which here is much more intense), but our understanding of these sources is still uncomplete and CRE producing synchrotron radiation are not observable. (1) Spiral galaxies should have synchrotron and dust emissions similar to the Milky Way, and should have a similar population of pulsars and SNR in the disk. We can look for an anisotropic signal against the background at small angular scale, but the presence of the thermal dust emission does not facilitate the background removal. In this case we can not decouple the effect generated by local sources from a Dark Matter signature. (2) Elliptical galaxies show a low dust and gas content. This means that both thermal emission and SNR generated by supernova explosions in a low density ISM are no longer important contaminants. Therefore these galaxies can be used as favorite targets for looking at a signature of Dark Matter annihilation or decay from the galactic halo.

In order to investigate the features we pointed out in this paper, spectral and polarimetric information, together with good angular resolution, would help. A spectro-polarimeter, or a polarimeter operating in different photometric bands, installed in the focal plane of a large far-IR telescope would be necessary. Because of the frequencies under investigation a space or a balloon-borne experiment could be preferred.

To have a more realistic estimate of the signals, in all the situations considered above, detailed calculations have to be done, including radiative transfer effects, in particular concerning polarized signals.

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